

D. PRZESTACKI, J. SIENIAWSKI, G. STAMBOLOV, P. LISIAK

AN OVERVIEW OF SELECTIVE LASER SINTERING TECHNOLOGIES

This paper presents an overview of the selective laser sintering (SLS) process of various materials. The influence of distinct scanning patterns and SLS process input parameters (e.g.: scanning rate, laser power, hatching distance) on the sintered materials' physical and technological properties was investigated. The classifications of SLS processes and scanning patterns were also presented. The literature survey revealed that sintered materials' density, shrinkage and dimensional accuracy are significantly affected by the scanning strategy, as well as selection of hatching distance and line energy. The research results presented in this work can be also applied to the appropriate selection of the SLS process strategy, enabling the improvement of sintered materials' physical and technological properties.

Key words: selective laser sintering, scanning strategies, densification, shrinkage

1. INTRODUCTION

Selective Laser Sintering (SLS) is defined as a Layer Manufacturing (LM) process that allows generating complex 3D parts by consolidating successive layers of powder material on top of each other [1, 2]. The binding is obtained by processing the selected areas using the thermal energy supplied by a focused laser beam (Fig. 1). Using a beam deflection system (galvano mirrors), each layer is scanned according to its corresponding cross section, as calculated from the CAD model. The deposition of successive powder layers with a typical thickness of 20 – 150 μm is realized using a powder deposition system [3].

The SLS technology was developed in the late 80's as a technique for Rapid Prototyping (RP) [4, 5]. At present, SLS, as well its derived technology – Selective Laser Melting (SLM) are applied also for Rapid Manufacturing (RM) and Rapid Tooling (RT). The RM and RT technologies concern the production of long-term consistent components (e.g. a dental implant) and tools (e.g. a plastic injection mould insert) made of a large variety of materials.

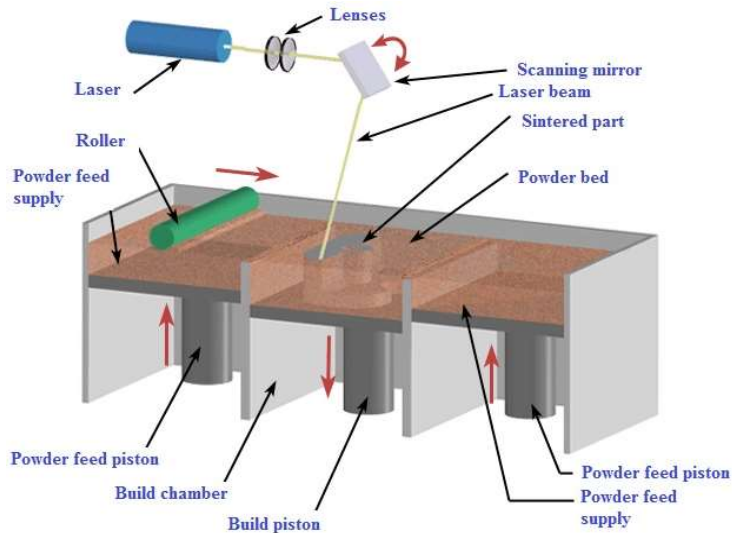


Fig. 1. Scheme of selective laser sintering process. Elaborated on the basis of [32, 33]

Generally, SLS is divided into two categories: the direct process of single powders and the indirect process of multiple powders [6,7]. In the direct process, a low melting point component is melted and employed as a matrix in which the higher melting point components are contained. In this process, a single powder with two different grain sizes (a fine and a coarse grains) or binary systems are applied. Typical binary phase systems include Ni-Cu, Fe-Cu and Cu-Pb/Sn [8]. The disadvantage of the above processing routes is that the components produced exhibit the mechanical properties and characteristics of their weakest composite phase, thus lacking the full mechanical functionality required for heavy-duty tasks [9]. Nevertheless, the direct SLS technique is extensively used to sinter the polymer [10–12], metal [13,14] even ceramic [15]. The indirect SLS uses a polymer coating of about 5 μm in thickness for metal powders and ceramics. The metal powder particles are coated with the polymer and the action of the laser melts the polymer, bonding the metal particles together to produce a green part. However, after this process, the post-treatment in the oven is needed, in order to remove the polymer and sinter particles by creating a metal-metal link.

It is worth pointing out that the extension of Selective Laser Sintering is Selective Laser Melting (SLM) process, which enables the production of functional metallic parts with high density. The substantial differences of the SLM in comparison to SLS technique are the application of an integral powder metal without adding low melting point elements, and necessity to provide a much higher energy density, needed for the fusion of powders.

During the SLS and SLM process the laser beam/powder/substrate system involves complex phenomena such as absorption, reflection, radiation and heat

transfer, phase transformations, fluid flow driven by surface tension gradients and mass transfer within the molten pool, as well as the chemical reactions [16]. Thus, the modification of the process input parameters, e.g.: scanning rate, laser power, hatching distance or scanning pattern can cause various undesirable effects as geometrical irregularity of the sintered track [17], balling effect [18] or an insufficient density of the sintered material [19, 20]. Therefore, this paper focuses on the literature survey related to the dependencies between the SLS process' strategies and the sintered materials' physical and technological properties. The deliberations presented in this work can be the starting point to further research focused on the selection of optimal SLS process input parameters and strategies, enabling the improvement of product's exploitation properties.

2. CLASSIFICATION OF LAYER MANUFACTURING PROCESSES

According to the work [21], Rapid Manufacturing and Rapid Tooling technologies can be classified in a number of ways.

The most frequently, layer manufacturing technologies are classified in accordance with materials they process. However, the authors of the work [3] divided the SLS/SLM technologies, in the aspect of the binding mechanism. Therefore, the general classification of the SLS processes can be presented in Figure 2.

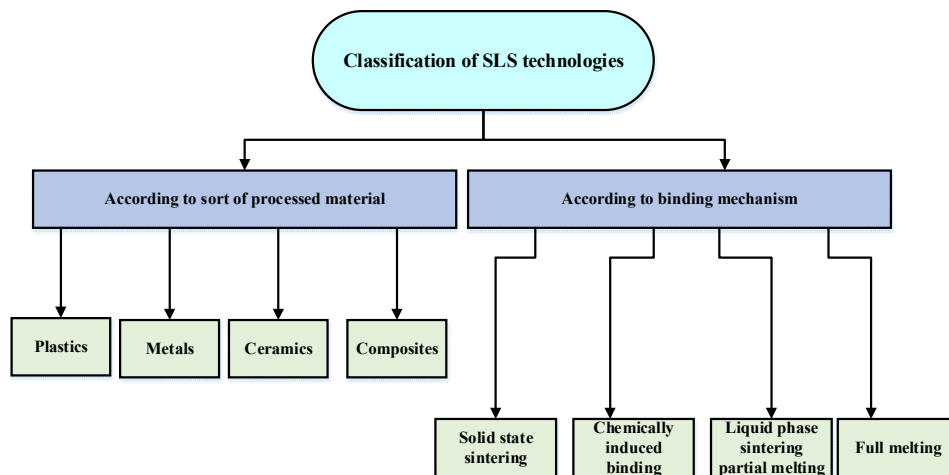


Fig. 2. Classification of SLS technologies. Elaborated on the basis of [3]

According to the binding mechanism, SLS technologies (and derived technologies like SLM and DMLS) can be classified in four categories. However

it has to be noticed that this classification is not absolute and the borders are not always very clear.

The first one is Solid State Sintering (SSS), which is a thermal process that occurs between the material's melting temperature (T_{melt}) and a half of this value ($T_{melt}/2$). During the SSS process, the most important phenomenon is diffusion [22]. The main advantage of Solid State Sintering is that a wide variety of materials can be processed this way.

During the chemically induced binding, no binder elements are applied and the laser-material interaction times are very short, thus excluding the diffusion processes occurring in Solid State Sintering. The examples of the products made by chemically induced binding are SiC and Al₂O₃ ceramic parts [23].

Most of Liquid Phase Sintering – partial melting techniques combine a structural material remaining solid throughout the process and a binder material being liquefied. This technology can be applied for the manufacturing of the metal-metal and metal-ceramic composites [24, 25].

Full Melting (FM) process was driven by the need to produce near full dense objects, with mechanical properties comparable to those of bulk materials and by the desire to avoid lengthy post processing cycles. During the FM process, both polymers and metals can be completely molten by a laser beam.

3. SCANNING PATTERNS DURING SLS/SLM TECHNOLOGY

The significant factor influencing the technological effects of the SLS/SLM processes is scanning pattern (strategy) of the laser beam. Literature survey reveals that during the SLS/SLM technology of various materials, distinct scanning patterns can be applied. The listing of the exemplary strategies is presented in Figure 3. The raster patterns are typically applied in Selective Laser Sintering and Selective Laser Melting processes [26]. The Figure 3a depicts short raster pattern in X direction, Figure 3b long raster pattern in Y-direction and Figure 3c scanning pattern alternating from layer-to-layer, starting with a short raster pattern for the first layer. In this case, the scan line spacing in X- and Y-direction is equal.

The spiral patterns (Figs. 3d, e) can be applied during the Laser Solid Forming (LSF) and Shape Deposition Manufacturing (SDM) [27, 28].

The fractal pattern (Fig. 3f) was developed directly for the LSF processes, in order to decrease the temperature gradient during the material's forming.

In other scanning patterns the part area is divided in small rectangular sectors (Figs. 3g, h). The order in which these sectors are being scanned can be successive or according to the least heat influence between the scanned sectors. The successive scan order starts with a line X scanning of the sector at the left bottom of the part. The next sector (at the right) is scanned with a line Y pattern, the next again with line X, etc. The least heat influence method (Fig. 3h) starts at

a randomly selected sector. Next the sector which is least heated is scanned and so on. Between the subsequent sectors the orientation of the line scan is alternated between X and Y [26].

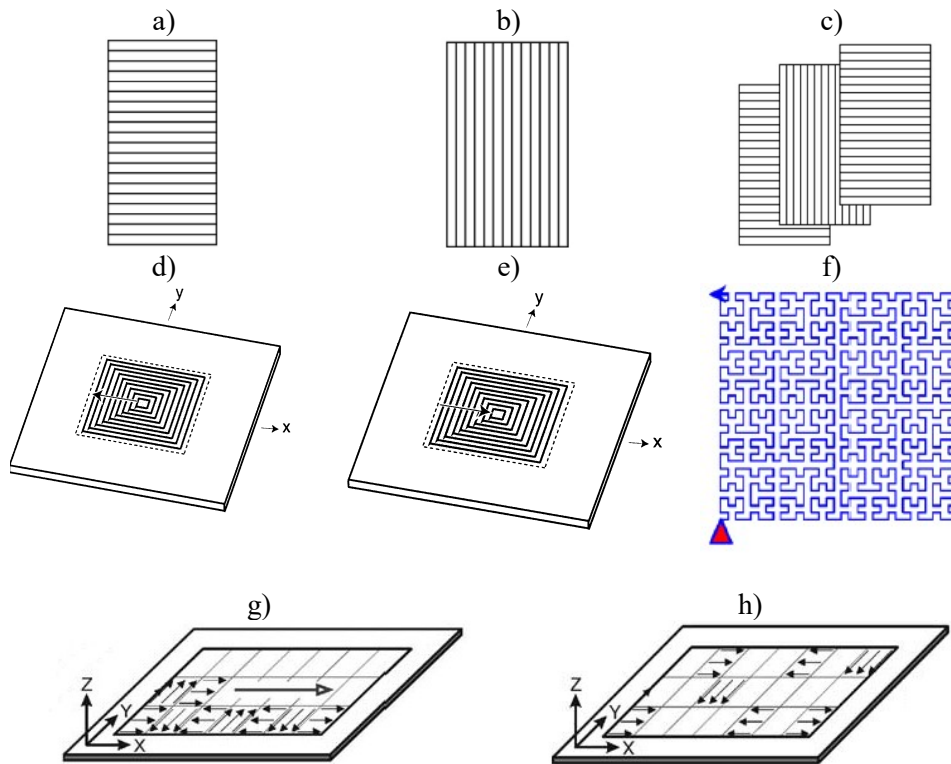


Fig.3. The examples of scanning patterns during SLS/SLM technologies: a) raster in X-direction; b) raster in Y-direction; c) raster sorted alternating in X- and Y- direction; d) spiral (offset in); e) spiral (offset out); f) fractal; g) scanning of successive sectors; h) scanning of least heat influence between sectors. Elaborated on the basis of [19, 26, 27, 28]

It is also worth to mention that manufacturing of injection molds can be made with SLS strategy developed by EOS GmbH company [31]. With the application of this strategy it is possible to distinct in product the outside layer with high mechanical properties which decide about injection mold's wear resistance, as well as an inside layer which gives proper shape and core material usually with relatively high porosity and lower density. This strategy enables the obtainment of satisfactory quality and decrease in time of manufacturing.

4. AN OVERVIEW OF FACTORS INFLUENCING FABRICATED MATERIALS' PROPERTIES

Many researches [7, 19, 29, 30] report that line energy is an essential parameter affecting sintered material's properties. This quantity can be defined as a quotient of laser power P to laser scanning speed v . According to [34] important factor affecting sintered material's densification is exposure time and energy density E described by the following equation:

$$E = \frac{P}{v \cdot s \cdot t} \quad (1)$$

where: s – distance between sintered paths, t – thickness of the layer.

In general, as the energy input increases (higher laser power, P , or lower scan rate, v), higher density is obtained. (see – Fig. 4). This dependency can be seen for various fabricated powders (Fig. 4a).

It can be also noticed that the density depends on the layer thickness and scan line spacing (hatching distance). Figures 4b and 4c show the effect of these parameters on the sintered density of iron powder. As it is seen, with increasing the layer thickness, lower density is achieved. Also, with decreasing the line scan spacing, higher density is obtained. This observation confirms that flow and solidification behavior of the melt is very strongly influenced by scan spacing. Furthermore, the research results, presented in [19] revealed that a progressive transition from a highly rippled surface to a smooth surface occurred with decreasing scan spacing. The rippled surface was accompanied by the formation of rows of vertically oriented pores.

Another effect which can be observed together with an increase of line energy is the growth of shrinkage depth (Fig. 4d). This parameter significantly affects sintered material's geometrical accuracy. The dependency between the line energy and shrinkage depth of fabricated material can be observed, during the laser sintering of iron [30], and composite powders [7]. This phenomenon is attributed to the bigger melting pool produced by the more energy input. These deliberations reveal that intensification of laser energy input (increasing laser power, decreasing scan rate, thinner layer thickness, and overlapping of scan lines) leads to higher densification. On the other hand, the growth of line energy induces the growth of unavoidable shrinkage depth. Therefore, the maintenance of laser energy input on the optimal level can improve sintered material's densification and geometrical accuracy.

Apart from sintering process' input parameters, the properties of fabricated materials are also significantly affected by the scanning patterns (strategies). The research carried out by the authors of Ref. [19] shows that the application of alternating raster strategy (depicted in Fig. 3c) results in a higher fractional density, independently of a part's dimensional ratio, in comparison to that obtained after the use of raster strategy in only one direction (see – Fig. 5).

Additionally, scanning strategy influences also fabricated part's geometrical accuracy. The authors of [26] measured the curvature of plates fabricated with the application of various scanning strategies, during SLM process (Fig. 6).

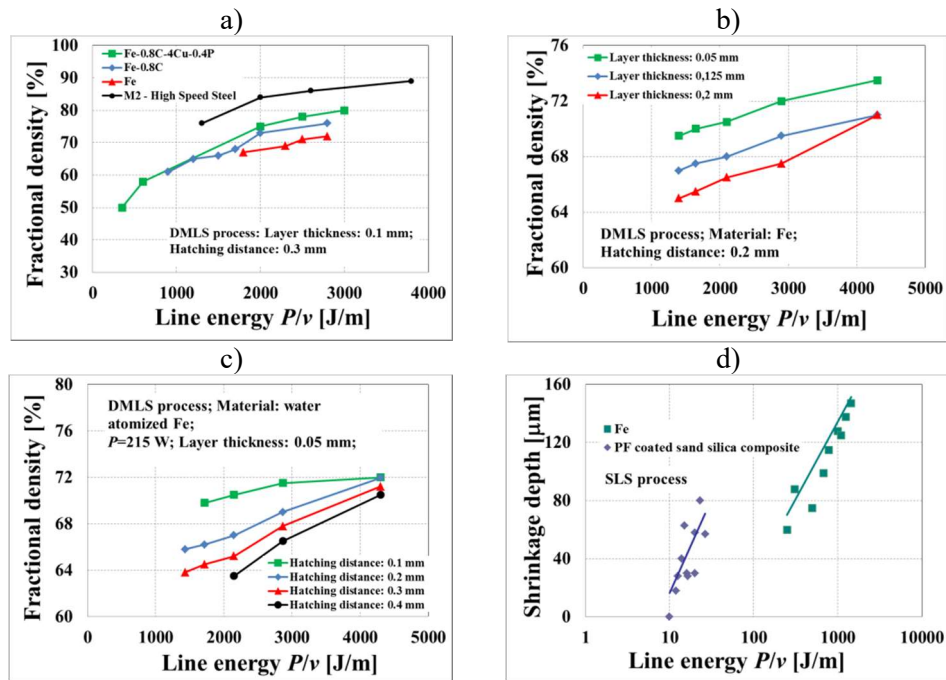


Fig. 4. The influence of the line energy on the: a) fractional density of various sintered powders [29]; b) fractional density of iron powders [29]; c) fractional density of iron powders depended also on hatching distance [19]; d) shrinkage depth [7, 30]

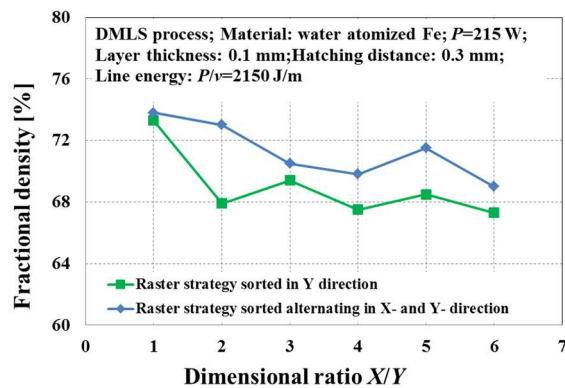


Fig. 5. Sintered density of iron powder dependent on scanning pattern for varying dimensional ratio. Elaborated on the basis of [19]

Results revealed that the application of raster strategy along X direction results in the smallest curvature in that direction, but the largest curvature in the

Y-direction (vice versa for the Y scanned part). Applying the scanning of successive sectors results in less deformation; there are rather small curvatures along X and Y directions. When comparing the successive sector scanning and the least heat influence strategy (LHI), it can be concluded that the successive method is preferable. A possible reason for the difference could be the higher thermal gradient obtained during LHI scanning.

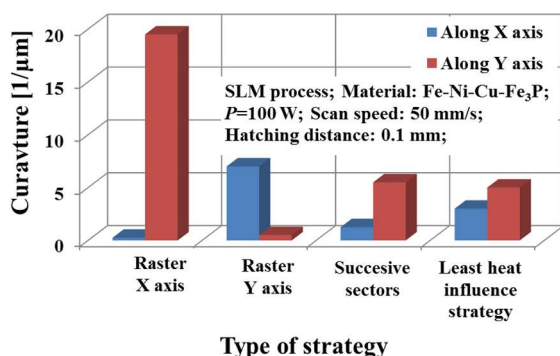


Fig. 6. The curvature of the fabricated part after SLM with various strategies. Elaborated on the basis of [24]

5. CONCLUSIONS

In this paper, an overview of selective laser sintering was presented. The influence of distinct scanning patterns and SLS/SLM process input parameters (e.g.: scanning rate, laser power, hatching distance) on the fabricated materials' physical and technological properties was investigated.

It was found that intensification of laser energy input (increasing laser power, decreasing scan rate, thinner layer thickness, and overlapping of scan lines) leads to higher densification. On the other hand, the growth of line energy induces the growth of unavoidable shrinkage depth. Therefore, the maintenance of laser energy input on the optimal level can improve sintered material's densification and geometrical accuracy.

Among the scanning patterns (strategies), the application of alternating raster strategy results in a relatively high fractional density of the fabricated material and the use of least heat influence strategy (LHI) can improve fabricated material's geometrical accuracy.

REFERENCES

- [1] Kruth J.P., Van Der Schueren B., Bonse J.E., Moren B.: Basic powder Metallurgical Aspects in Selective Metal Powder Sintering, *Annals of the CIRP* Vol. 45/1, 1996
- [2] Kruth J.P., Wang X., Laoui T., Froyen L., *Lasers and Materials in Selective Laser Sintering*, Proc. Int. Conf. on Laser Assisted Net Shape Engineering, 2001

- [3] Kruth J.P., Mercelis P., Van Vaerenbergh J., Froyen L., Rombouts M.: Binding mechanisms in selective laser sintering and selective laser melting, *Rapid Prototyping Journal*, Vol. 11, (1), (2005), 26 - 36
- [4] Bourell D.L., Marcus H.L., Barlow J.W., Berman J.J.: Selective laser sintering of metals and ceramics, *Int. J. Powder Metall.* 28 (4) (1992) 369
- [5] Kruth J.P.: Material in-process manufacturing by rapid prototyping techniques, *CIRP Ann.* 40 (2) (1991) 603–614
- [6] Campanelli S.L., Contuzzi N., Angelastro A., Ludovico A., D.: Capabilities and Performances of the Selective Laser Melting Process, *Capabilities and Performances of the Selective Laser Melting Process in: InTech, New Trends in Technologies: Devices, Computer, Communication and Industrial Systems*, Edited by Meng Joo Er (2010), 233 – 252
- [7] Liu F.R., Zhao J.J., Hang Q., He C., Chen J.M.: Processing and characterizations of 2%PF/silica sand core-shell composite powders by selective laser sintering with a higher transmittance fiber laser, *International Journal of Machine Tools & Manufacture* 60 (2012) 52–58
- [8] Lu L., Fuh J.Y.H., Wong Y.S.: *Laser-Induced Materials and Processes for Rapid Prototyping*, Kluwer Academic Publishers, ISBN 0792374002, (2001) Norwell, USA
- [9] Dewidar M.M., Lim J.K., Dalgarno K.W.: A Comparison between Direct and Indirect Laser Sintering of Metals. *Journal of Materials Sciences and Technology*, Vol. 24, No.2, 227-232, ISSN (2008) 1005-0302
- [10] Ho H.C.H., Cheung W.L., Gibson I.: Morphology and properties of selective laser sintered Bisphenol A polycarbonate, *International Engineering Chemistry Research* 42 (2003) 1850–1862
- [11] Yang J.S., Shi Y.S., Shen Q.W., Yan C.Z.: Selective laser sintering of HIPS and investment casting technology, *Journal of Materials Processing Technology* 209 (2009) 1901–1918
- [12] Caulfield B., McHugh P.E., Lohfeld S.: Dependence of mechanical properties of polyimide components on build parameters in the SLS process, *Journal of Materials Processing Technology* 182 (2007) 477–488
- [13] Das S.: Physical aspects of process control in selective laser sintering of metals, *Advanced Engineering Materials* 5 (10) (2003) 701–711
- [14] Patil R.B., Yadava V.: Finite element analysis of temperature distribution in single metallic powder layer during metal laser sintering, *International Journal of Machine Tools & Manufacture* 47 (2007) 1069–1080
- [15] Tang Y., Fuh J.Y.H., Loh H.T., Wong Y.S., Lu L.: Direct laser sintering of a silica sand, *Materials and Design* 24 (2003) 623–629
- [16] Yadroitsev I., Krakhmalev P., Yadroitsava I., Johansson S., Smurov I.: Energy input effect on morphology and microstructure of selective laser melting single track from metallic powder, *Journal of Materials Processing Technology* 213 (2013) 606–613
- [17] Niu H.J., Chang I.T.H.: Instability of scan tracks of selective laser sintering of high speed steel powder. *Scripta Materialia* 41 (1999), 1229–1234
- [18] Tolochko N.K., Mozharov S.E., Yadroitsev I.A., Laoui T., Froyen L., Titov V.I., Ignatiev M.B.: Balling processes during selective laser treatment of powders. *Rapid Prototyping Journal* 10, (2004) 78–87
- [19] Simchi A., Pohl.: Effects of laser sintering processing parameters on the microstructure and densification of iron powder. *Materials and Engineering A359* (2003) 119-128
- [20] Ma M., Wang Z., Gao M., Zeng X.: Layer thickness dependence of performance in high-power selective laser melting of 1Cr18Ni9Ti stainless steel. *Journal of Materials Processing Technology* 215 (2015) 142–150
- [21] Levy G.N., Schindel R., Kruth J.P.: *Rapid Manufacturing and Rapid Tooling with Layer Manufacturing (LM) Technologies, State of the Art and Future Perspectives*, *Annals of the CIRP*, Vol. 52/2, 2003
- [22] Van Der Schueren B.: *Basic Contributions to the Development of the Selective Metal Powder Sintering Process*, PhD thesis, University of Leuven, 1996

- [23] Klocke F., Wirtz H.: Selective Laser Sintering of Ceramics, Proc. Int. Conf. on Laser Assisted Net Shape Engineering, 1997
- [24] Kruth J.P., Peeters P., Smolderen Th., Bonse J., Laoui T., Froyen L.: Comparison between CO₂ and Nd:YAG lasers for use with Selective Laser Sintering of steel-copper powders, Revue International de CFAO et d'informatique graphique, Vol. 13 (4-5-6), 95-112, 1998
- [25] Laoui T., Froyen L., Kruth J.P.: Effect of mechanical alloying on Selective Laser Sintering of WC-9Co powder, Powder Metallurgy, Vol. 42(3), 203-205, 2000
- [26] Kruth J.P., Froyen L., Van Vaerenbergh J., Mercelis P., Rombouts M., Lauwers B.: Selective laser melting of iron-based powder, Journal of Materials Processing Technology 149 (2004) 616–622
- [27] Yu J., Lin X., Ma L., Wang J., Fu X., Chen J., Huang W.: Influence of laser deposition patterns on part distortion, interior quality and mechanical properties by laser solid forming (LSF), Materials Science and Engineering A 528 (2011) 1094–1104
- [28] Nickel A.H., Barnett D.M., Prinz F.B.: Thermal stresses and deposition patterns in layered manufacturing, Materials Science and Engineering A317 (2001) 59–64
- [29] Simchi A.: Direct laser sintering of metal powders: Mechanism, kinetics and microstructural features, Materials Science and Engineering A 428 (2006) 148–158
- [30] Liu F.R., Zhang Q., Zhou W.P., Zhao J.J., Chen J.M.: Micro scale 3D FEM simulation on thermal evolution within the porous structure in selective laser sintering, Journal of Materials Processing Technology 212 (2012) 2058–2065
- [31] http://www.eos.info/additive_manufacturing
- [32] Krol M., Kujawa M., Dobrzanski L.A., Tanski T.: Influence of technological parameters on additive manufacturing steel parts in Selective Laser Sintering. Archives of Materials Science and Engineering, Vol. 67, Issue 2, (2014) 84 – 92
- [33] <http://www.custompartnet.com/wu/selective-laser-sintering>
- [34] Krol M., Dobrzanski L.A., Reimann L., Czaja I.: Surface quality in selective laser melting of metal powders. Archives of Materials Science and Engineering, Vol. 60, Issue 2, (2013) 87 – 92

PRZEGLĄD TECHNOLOGII SELEKTYWNEGO SPIEKANIA LASEROWEGO

S t r e s z c z e n i e

W pracy dokonano przeglądu literaturowego, dotyczącego technologii selektywnego spiekania laserowego. Zaprezentowano wyniki badań dotyczące wpływu strategii oraz parametrów wejściowych procesu (np.: prędkości wiązki lasera, mocy lasera, odległości pomiędzy ścieżkami wiązki) na właściwości fizyczne i technologiczne otrzymanych spieków. Dokonano również klasyfikacji procesów SLS i niezbędnych do ich realizacji strategii.

Przegląd literatury ukazał, że gęstość, skurcz oraz dokładność geometryczna spieków w istotnym stopniu zależą od doboru strategii, odległości pomiędzy ścieżkami wiązki lasera i energii liniowej. Wyniki badań zaprezentowane w pracy mogą również stanowić punkt wyjścia do dalszych badań, dotyczących poprawy właściwości fizycznych i technologicznych wytwarzanych spieków.

Słowa kluczowe: selektywne spiekanie laserowe, strategie spiekania laserowego, zagęszczenie, skurcz